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14. ABSTRACT
Slow and fast light schemes are attractive for many applications including optical signal processing and RF phased array antennas. Semiconductor based schemes offer electrical control of velocity at very high bandwidths in an extremely compact device. Further they operate at room temperature and can be easily integrated into various optical systems. In this program, we used ultrafast nonlinearities in semiconductor optical amplifiers (SOAs) to achieve tunable time shifts at THz frequencies. In particular, we leveraged the spectral hole burning phenomena and demonstrated fast light in quantum well (QW) and quantum dot (QD) SOAs. The research included both theoretical and experimental efforts. Theoretical work was developed to understand and simulate experimental results and to optimize device designs. We introduced a novel pulse compression technique to reduce the pulse width to 100 fs to efficiently use ultra-fast nonlinearities in SOAs to achieve a large and cascadable delay. We implemented a novel chirped pulse scheme and obtained the largest advance-pulse-product of 10.7 with THz bandwidth. We demonstrated slow and fast light with GHz RF signal in QW/QD SOAs using coherent population oscillation and four-wave mixing. We also demonstrated

15. SUBJECT TERMS
RF Photonics, Optical True Time Delay, Slow Light, Optics, Quantum Dot, Semiconductor Optical Amplifiers

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Final Report
Fast Light in Quantum Dot and Well Semiconductor Optical Amplifiers
Contract Number: FA9550-07-1-0325; Program duration 5/1/07-9/30/10

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1. Objectives:

Slow and fast light schemes have shown to be an attractive option for applications including optical buffering, optical signal processing, and RF phased array antennas. By using various physical processes in semiconductor optical amplifiers (SOAs), slow and fast light has been demonstrated at frequencies ranging from GHz to THz. The SOAs offer advantages of compactness, room temperature operation and easy integration with optical components and electronics circuits.

In this program, we used ultrafast nonlinearities in SOAs to achieve tunable time shifts at THz frequencies. In particular, we leveraged the spectral hole burning (SHB) phenomena and demonstrated fast light in quantum well (QW) and quantum dot (QD) SOAs. The research program included both theoretical and experimental efforts. Theoretical frame work was developed to understand and simulate experimental results and serves as guidance to optimize the design of our devices. We also introduced a novel pulse compression technique to reduce the pulse width to 100 fs to efficiently use ultra-fast nonlinearities in SOAs to achieve a large and cascadable delay.

We have carried out the proposed experimental implementation of novel chirped pulse scheme and obtained the largest advance-pulse-product of 10.7 with THz bandwidth. This was well received and resulted in several invited talks and several invited papers. We have demonstrated slow and fast light with continuous RF signal (GHz bandwidth) in both QW and QD SOAs using coherent population oscillation and four-wave mixing. We have also demonstrated cascading of SOA devices in a loop condition for the scaling law of slow and fast light with 12 ps pulses.

2. Accomplishments and New Findings:

2.1 THz Fast Light

Slow and fast light devices built with semiconductors are compact, compatible with communication wavelengths, easily integrated with other components and can operate on signals with THz bandwidth [1,2]. Our recent work has concentrated on fast light from ultrafast intraband nonlinearities such as carrier heating (CH) and spectral hole burning (SHB) [2]. In addition, a new effort to extend the results of ref. 2 by adding and then removing a frequency chirp to the pulses [3]. We show an improvement of advance-bandwidth product (ABP) from 2.5 pulses to more than 10 pulses [4].

When an ultrafast pulse enters the SOA, it immediately begins removing carriers via stimulated emission. This leaves a “hole” in the gain spectrum at the pulse wavelength. Heuristically, we expect such a dip in gain to be accompanied by a fast light dispersion. As the SOA gain is increased, the hole becomes deeper, so the advance may be tuned by changing the bias current. The width and persistence of hole are determined by the carrier-carrier scattering time. Due to

the sub-picosecond nature of carrier-carrier scattering, we expect these effects to be most efficient with THz-bandwidth pulses. However, as the pulse is amplified, the hole depth cannot reach beyond transparency. The shape of the hole and the pulse spectrum are altered and distortion sets in. To mitigate this effect, we propose and test a “chirp and compensate” scheme, whereby the pulse is chirped out with a linear group delay dispersion such that different spectral components enter the device at different times and interact with carrier populations at different energy levels. At the output the pulse is then recompressed with a chirp of the opposite sign, realizing a large ABP.

Experimental Results

A mode-locked laser from Calmar-Optcom generates pulses at 1550 nm with a 20 MHz repetition rate. The pulses are split into a signal and a reference. The reference passes through a fixed delay and into an optical cross-correlator. The signal propagates through a chirper, the SOA, a second chirper of opposite sign called the counter-chirper, an EDFA, and then into the other arm of the cross-correlator. The chirper and counter-chirper are both grating-based devices which leave the spectrum of the pulse unchanged but stretch or compress the pulse in time. The initial chirp of the pulse can be either positive, with red spectral components entering the SOA first, or negative, with blue components entering first. It is important to note that the chirp and counter-chirp are fixed while the SOA bias is tuned.

Figure 2 shows the cross-correlation traces as the SOA bias is swept for a 470 fs pulse stretched to 10 ps with two different signs of input chirp. The top (blue) trace is the blue-first case while the bottom (red) is the red-first case. As the SOA gain is swept from near transparency to maximum gain the blue-first pulse advances 2.4 ps (5.2 pulses). The residual broadening of the pulse after recompression by the counter-chirper is quantified by a Gaussian fit to the peak. From the fit and from the root-mean-square width of the reference pulse, the broadening is calculated and is shown to be no more than 45% for either chirp. When the input chirp is switched to red-first, the pulse experiences a *delay* of 1.86 ps (3.9 pulses) as the current is increased. This is unexpected, as a hole in a gain spectrum should lead to fast light. This delay can be understood by examining the pulse spectra shown in Fig. 3. Because the red spectral components enter the SOA first, they are preferentially amplified and the spectrum experiences a red shift. The counter-chirper recompresses the pulse by delaying the red components with respect to the blue. Thus the net red shift of the spectrum causes a delay which dominates over the advance. Similarly, the blue-first pulse will be blue-shifted, but in this case the counter-chirper delays blue components. Thus the blue-first pulse will also experience some delay upon recompression. However, the blue shift is less than the red shift and the advance from intraband effects dominates over the delay from recompression. This also implies that the measured advance is smaller than the actual advance produced by the intraband effects. The origin of the discrepancy between the blue- and red-first wavelength shift is still unclear, but one possible explanation is the tendency of the self phase modulation (SPM) from the intraband nonlinearities to red shift the pulse. Figure 4 shows a schematic for a system to make use of the delay caused by the spectral shift to extend the tunable ABP. When the 2×2 switches are in the bar configuration the pulses are negatively chirped before entering the SOA and positively chirped to recompress. In this case the pulse advances as SOA bias increases. When the switches are crossed, the pulse is positively chirped and experiences a tunable delay.

A still shorter initial pulse may be used to further increase the ABP. In Fig. 5, a 370 fs pulse has been chirped out to 14 ps. This pulse advances by 2.4 ps (6.5 pulses). When the sign of the chirp

is reversed, the pulse is delayed by 1.56 ps (4.2 pulses), for a total A/DBP of 10.7 pulses. This is the largest advance reported for sub-picosecond pulses to date.

Figure 6 shows a summary of our results for different amounts of chirp. The maximum achieved ABP is plotted against the dispersion parameter *D*, calculated from the pulse broadening. Note that because *D* is defined in terms of λ, positive *D* is equivalent to negative chirp. The ABP is linearly related to *D*, with the transition between delay and advance occurring at -0.6 ps/nm.

2.2 Slow Light using QD and QW SOAs

Slow and fast light in SOAs using coherent population oscillation and four-wave mixing have been investigated both in theory and experiments [5-8]. In this work, we demonstrated and compared slow light (in absorption regime) and fast light (in gain regime) both in QW and QD SOAs. We found that QW-SOAs can have about two time larger delay/advance compared with QD-SOAs due to larger tuning range of modal gain. In addition, QW-SOA has higher bandwidth because of more rapid inter-band carrier recombination rate. In QD-SOA, slow and fast light have been compared between ground state transitions and excited state transitions. In our tested QD-SOA sample, excited state has larger differential gain, which results more phase shifts compared with ground state transition. According to our results, differential gain is one of the key parameters for large ABP in SOAs. With the advancement of more homogeneous QD growth, we expect further improvement of ABP in QD-SOAs.

In order to demonstrate the scaling-law of cascading multiple SOAs, we have experimented slow and fast light in a loop configuration [9]. By sending the pulse signal into a SOA in a loop, we demonstrated almost liner increase of ABP with number of cascading devices up to 12 round traveling in a loop.

Experimental Results

Slow and fast light in both QW-SOA and QD-SOA are compared with the same condition. An input signal is RF modulated generating two sidebands (probes) around the center optical frequency (pump). These two sidebands probes interact with center pump frequencies via coherent population oscillation. Two probe themselves interacts their counterpart via four-wave mixing. In absorption regime both of these interaction generates absorption dip resulting slow light (in gain regime, fast light). Figure 7 shows phase-shifts of 1.0 GHz modulated signal in QW-SOA. From transparency current, slow light (in absorption) and fast light (in gain) are observed both in phase measurement in network analyzer and time domain measurement in oscilloscope. The modulation frequency response of measurement agrees very well with the theory we have developed [5-7]. The same measurement is demonstrated in QD-SOA [8]. Figure 8(a) shows gain spectrum of tested QD-SOA. The ground state transition is around 1560 nm and the first excited state is around 1530 nm. As shown in gain spectrum and Fig.8 (b), differential gain of the excited state is larger than that the ground state. As a result, phase shift of excited state is almost twice of the ground state signal. This agrees well with our previously derived relation of phase shift with the modal gain of the SOA [5-8]. In theory, ideal QD have sharp density of states with potentially very large differential gain. With the advancement of more homogeneous QD growth, QD-SOA has potential to outperform the QW-SOA for larger ABP.Figure 9 (a) shows experimental results of scaling-law of cascading multiple SOAs. A 12 ps pulse signal generated by mode-lock laser is coupled in to a ring loop with a single QW-SOA. For each round trip, pulse is measured for time delay/advance by varying SOA injection current. The detailed experiment setup is explained in [9]. From this experiment, we have demonstrated that the linear scaling law holds for ABP in SOAs cascading up to 12 passes without any noticeable saturation. At 12 loops, 12 ps signal can be advanced by 8.3 pulses.

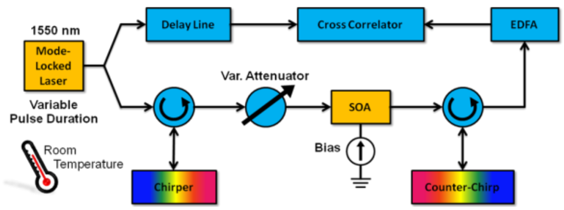

Fig. 1. Experimental setup. A mode-locked laser produces sub-picosecond pulses. The chirper and counter-chirper are grating-based devices which preserve the pulse spectrum. The chirper stretches the pulse with either positive or negative chirp while the counter-chirper applies the opposite chirp to recompress the pulse. SOA bias current is swept and the temporal shift of the pulse is measured via optical cross-correlation.

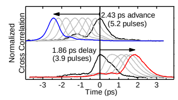

Fig. 2. Cross-correlation traces as SOA bias is increased from transparency (black trace) to maximum. The initial pulse is 470 fs and is chirped out to 10 ps. Negatively chirped pulses are advanced with ABP=5.2 (top), while positively chirped pulses are delayed with DBP=3.9 (bottom).

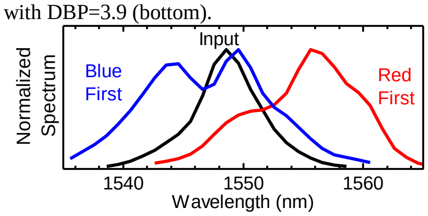

Fig. 3. Pulse spectra before SOA (black) and after SOA for both red-first (red) and blue-first (blue) input chirp at an SOA bias of 100 mA. The blue spectral components of the blue-first pulse are preferentially amplified by the SOA, blue-shifting the spectrum. Similarly the positively chirped pulse is red shifted. SPM increases the red shift and decreases the blue shift.

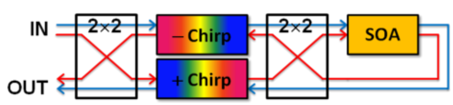

Fig. 4. A possible scheme to realize delay and advance in the same sub-system. Increasing SOA bias current will advance pulses when the switches are in the bar configuration and delay pulses when they are crossed.

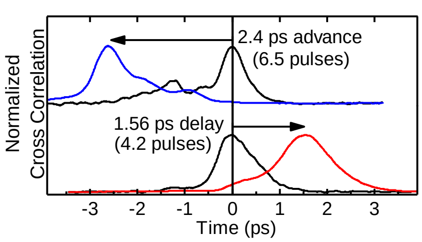

Fig. 5. Cross-correlation traces for a 370 fs initial pulse chirped out to 14 ps. Negatively chirped pulses (top) advance 2.4 ps resulting in a ABP=6.5, while positively chirped pulses (bottom) are delayed by 1.56 ps with a DBP=4.2. The total time shift is 10.7, the largest reported for sub-ps pulses.

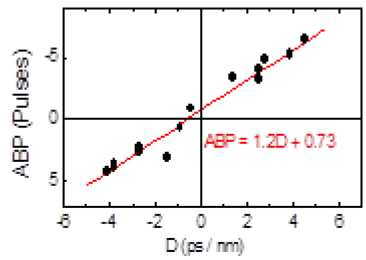

Fig. 6. Maximum achieved ABP as a function of pulse chirp, quantified here with the dispersion parameter *D*. Note that because *D* is defined in terms of wavelength it is positive when the chirp is negative and vice versa. The trend is linear, with a transition from advance to delay at -0.6 ps/nm.

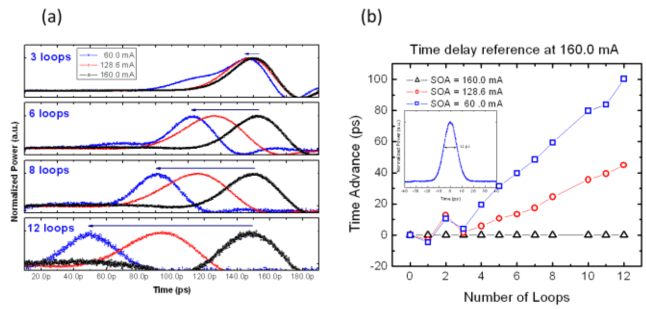

Fig. 7. (a) Phase shift of continuous 1.0 GHz modulated RF signal in QW-SOA. By switching from absorption to gain regime in SOA, 110 degrees phase shift is observed. (b) Time domain signal of the same QW-SOA demonstrating slow light in absorption and fast light in gain.

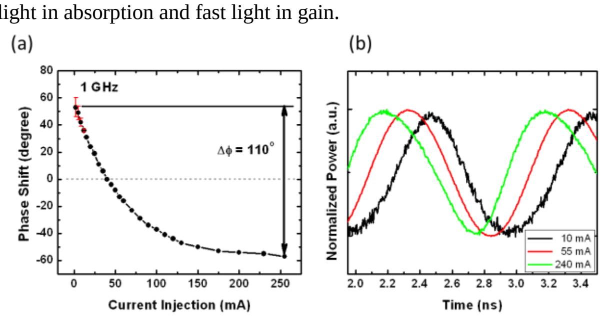

Fig. 8. (a) Gain spectrum of QD-SOA. The ground state transition is at around 1560 nm whereas excited state transition is at around 1530 nm. (b) The comparison between the ground-state and the first excited-state transition for the phase shift with modulation frequency 1.0 GHz and the small signal modal gain as a function of the injection current from the transparency.

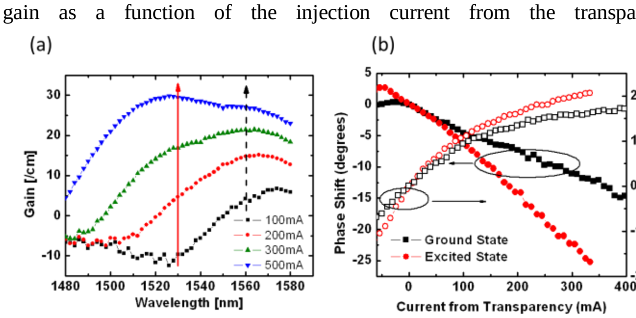

Fig. 9. (a) Electrical tuning of pulse shift for different numbers of loops as signal passes (At 12 loops, signal pass through SOA for 12 times). (b) Scaling law of time advance as a function of loops references at SOA injection is 160 mA. Almost linear scaling law has been observed.

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4. Personnel Supported:

1. Forrest Sedgwick, post-doc, UC Berkeley
2. Bala Pesala, graduate student, UC Berkeley
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4. Akira Matsudaira, graduate student, Univ. of Illinois, Urbana-Champaign

5. Journal Publications:

1. D. Nielsen, A. Matsudaira, S. L. Chuang, B. Pesala, F. Sedgewick, and C. J. Chang-Hasnain, “Fast-light to slow-light switching in a laser cavity,” IEEE Photon. Technol. Lett., vol. 23, no. 14, pp.971-973, 2011.
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3. P. K. Kondratko, A. Matsudaira, S.-W. Chang, and S. L. Chuang, “Slow and Fast Light in quantum-well and quantum-dot semiconductor optical amplifiers”, book chapter in

Comprehensive Semiconductor Science & Technology, Ed. Pallab K. Bhattacharya, Elsevier, 2010.

4. Ye Zhou, Michael C. Y. Huang, Christopher Chase, Vadim Karagodsky, Michael Moewe, Bala Pesala, Forrest Sedgwick, Connie J. Chang-Hasnain, "High-Index-Contrast Grating (HCG) and Its Applications in Optoelectronic Devices," IEEE Journal of Selected Topics in Quantum Electronics, Vol. 15, No.5, pp. 1485-1499, Sept.-Oct. 2009.
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6. Interactions/Transitions:

6.1 Participation/presentations at meetings, conferences, seminars, etc.

1. Bala Pesala, Vadim Karagodsky and Connie Chang-Hasnain, “Ultra-compact low loss photonic components using high-contrast gratings”, International Conference on Optics and Photonics (ICOP ‘09), Chandigarh, India, October 30 - November 1, 2009.
2. Bala Pesala, Vadim Karagodsky, Fumio Koyama and Connie Chang-Hasnain, “Novel 2-D High-Contrast Grating Hollow-Core Waveguide”, Conf. on Lasers and Electro-Optics (CLEO ’09), Baltimore, MD, May 31 - June 5, 2009.
3. Ye Zhou, Vadim Karagodsky, Forrest G . Sedgwick, Connie J . Chang-Hasnain, “Ultra-Low Loss Hollow-Core Waveguides Using High-Contrast Gratings,” Conf. on Lasers and Electro-Optics (CLEO ’09), Baltimore, MD, May 31 - June 5, 2009.

4. Bala Pesala, Forrest G. Sedgwick, Alexander Uskov and Connie Chang-Hasnain, “Theory and Experiment of chirped-pulse THz slow and fast light in semiconductor optical amplifiers”, Frontier in Optics (FiO ‘08)/Laser Science XXIV (LS) Conference, New York, U.S.A, October 19-23, 2008.
5. Bala Pesala, Forrest G. Sedgwick, Waison Ko and Connie Chang-Hasnain, “Electrically tunable fast light of 86fs pulses in Semiconductor Optical Amplifiers”, OSA topical meeting, Boston MA, USA 13-16 July 2008.
6. Forrest G. Sedgwick, Bala Pesala and Connie J. Chang-Hasnain, “Chirped-Pulse Slow and Fast Light in SOA with a Record Delay-Bandwidth Product of 10.7,” Conference on Lasers and Electro-Optics (CLEO), San Jose, CA, USA, 4-9 May 2008
7. Bala Pesala, Forrest G. Sedgwick, Alexander V. Uskov and Connie J. Chang-Hasnain, “Novel chirp-enhanced tunable fast light of ultra-short pulses in semiconductor optical amplifiers”, Optical Fiber Conference, San Diego, CA, 24-28 February 2008.
8. Alexander V. Uskov, Forrest G. Sedgwick, Bala Pesala, and Connie J. Chang-Hasnain, “Ultrafast Nonlinear Group Index in Semiconductor Optical Amplifiers for Slow and Fast Light,” OSA Annual Meeting, Frontiers in Optics, San Jose, CA, 17-20 September 2007
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10. Forrest G. Sedgwick, Bala Pesala, Jui-Yen Lin, Connie J. Chang-Hasnain and Tony Lin, “Increase of Fractional Advance in THz-Bandwidth Fast Light by Pulse Chirping in an SOA,” OSA topical meeting on slow and fast light, Salt Lake City, Utah, USA, 8-11 July 2007.
11. Bala Pesala, Forrest G. Sedgwick, Alexander V. Uskov, Connie Chang-Hasnain and Tony H. Lin, “THz Tunable Slow Light and Fast Light of Ultrashort Pulses in Semiconductor Optical Amplifiers”, OSA topical meeting on slow and fast light, Salt Lake City, Utah, 8-11 July 2007.
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13. F. G. Sedgwick, Bala Pesala, Jason Lin, Wai Son Ko, Xiaoxue Zhao, and C. J. Chang-Hasnain, “THz Tunable Slow Light in Semiconductor Optical Amplifiers”, Optical Fiber Communications Conference, Anaheim, California, March 25-30 (2007)

6.2 Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates, and name(s) of principal individuals involved.

None

1. Transitions.

None

7. New discoveries, inventions, or patent disclosures. (If none, report None.)

None

8. Honors/Awards:

1. Connie Chang-Hasnain, IEEE David Sarnoff Award 2011
2. Forrest Sedgwick, Leon Chua Award, EECS, University of California, Berkeley, 2009.
3. Bala Pesala, Demetri Angelakos Award, EECS, University of California, Berkeley 2009
4. Connie Chang-Hasnain, Humboldt Research Award, Alexander von Humboldt Stiftung Foundation 2009
5. Connie Chang-Hasnain, Guggenheim Memorial Foundation Fellowship, 2009
6. Connie Chang-Hasnain, Microoptics Award, Microoptics Conference (MOC), The Japan Society of Applied Physics 2009
7. Bala Pesala, Best Paper of Topical Meeting, OSA Slow and Fast Light Topical Meeting, 2007.
8. Connie Chang-Hasnain, *Nick Holonyak Jr. Award*, Optical Society of America, 2007.

INSTRUCTIONS FOR COMPLETING SF 298

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